SkuTek Digital Data Acquisition Systems

Wojtek Skulski

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Summary of This Presentation

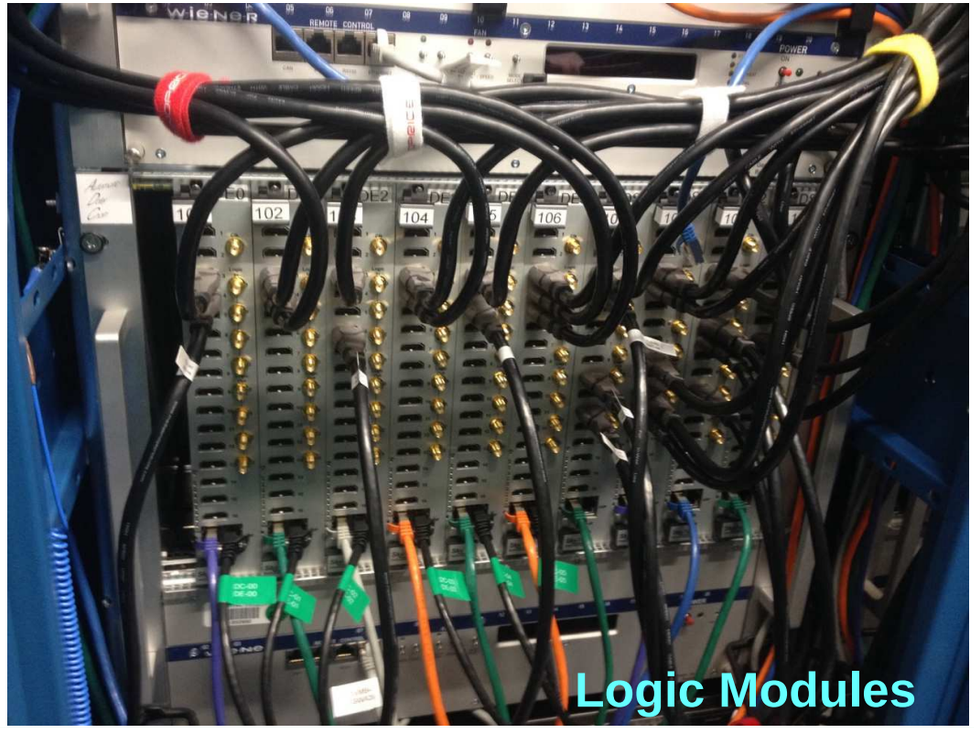
- **Multichannel DAQ for large experiments**.
  - **High quality, low noise,** and excellent **pulse response**
  - ADC **nonlinearity** measurement and **correction**
- **We offer high channel density DAQ** scalable from 32 channels up to thousands.
- **Table-top 2-channel Digitizer and MCA for R&D, student labs, or small experiments**.
  - We are showing this table top device at the end of this presentation.

American Made
Premium Quality

R&D funded by the DOE
Office of Nuclear Physics

We Delivered **Large Scale DAQ**: LUX-Zeplin Data Acquisition

- LUX-Zeplin is the world's largest Dark Matter Search liquid xenon two-phase TPC (10 ton LXe).
- We delivered **1,632 channels** of the DAQ (left photo) plus **26 Logic Boards** (right photo) to the LZ Collaboration.
- This Summer we delivered **additional 900 channels**, plus **10 Logic Boards**.
- The DAQ was deployed in Sanford Underground Research Facility (SURF) at -4850' in Summer 2019.
- DAQ is collecting signals since November 2019 without any failures. https://arxiv.org/abs/2405.14732



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Summary of our DAQ

- **Premium features of SkuTek DAQ**.
  - **High quality, low noise,** and excellent **pulse response**
  - ADC **nonlinearity** measurement and **correction**
- **We offer high channel density DAQ** scalable from 32 channels up to thousands. Example: LZ DAQ.
  - The complete solution: from detectors **all the way** to the High Performance Computing centers.
  - Digitizers, trigger logic units, data collection computers, readout, and data management software.
- You will receive a **tested DAQ** including (optional) **Data Collector computers**.
- 80 Gbps data collector for a large DAQ
- 10 Gbps data collector for smaller DAQ
- FPGA-based "**UDP Cannon**" for stress testing the DAQ networks.
- **Software**:
  - Data management, high performance data writing, Globus file transfer, SkuTek utilities.

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Highligths of Useful DAQ Features

- We are providing useful features developed over many years.
- High quality, low-noise analog signal processing.
  - We achieved the highest signal quality, limited only by the ADC nominal performance specified in the ADC data sheet.
- 4 logic in, and 4 logic out per board, whose functions are implemented in firmware: trigger, veto, busy, ….
  - Can input or output either NIM or LVTTL (hardware switch on each board).
- Analog signal synthesis and reconstruction with every board: 2 analog outputs with 14 bits @ 100 MHz.
  - Any input can be routed to an oscilloscope without unplugging the input cable.
  - Internal FPGA signals can be routed to the scope and examined.
- Local Linux with every board:
  - Absence of any VME controller. All the access is via Ethernet individually for every board.
  - Local Linux SBC on every board: setup, monitoring, remote FPGA re-programming over Ethernet.
  - Linux SBC was derived from, and it is highly compatible with a popular BeagleBone Black.
  - Remote FPGA firmware diagnostics over Internet. Works across the continent.
  - Convenient readout using Linux SBC, up to about ~15 MB/s. **It may be sufficient for low rate experiments!**
  - Local Linux is the full Debian with all the features: web server, Python, Jupyter, networked file system,…
- In addition to Linux Ethernet, there is an independent **1G Ethernet readout** directly from firmware.
- In addition to the above, a Rear Transition Module will add **10G Ethernet**, 8 more NIM I/O's, and other features.

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Part I: Our Proposition.

The details are negotiable.

We propose that the customer adopts our *entire* infrastructure, which was tightly knit for seamless operation.

- Five parts: hardware, firmware, software, fast streaming readout, and data management.
- Our frameworks will save the customer an enormous development effort.
- Either party can be tasked with customizing the firmware, software, or fast streaming readout.
- If "either party" is ourselves, then we will propose a contract to perform customization.
- If "either party" is the customer's team, then we will pass the information to the customer.

- The "fast streaming readout" provides formats, links, and the data collector computers.
- The customer can employ their own computer infrastructure. In such a case our collector computers will provide a useful starting point for the customer's solutions and customizations.
- A reasonable after-sale support will be provided for free. (Basically, we will answer questions to let the customer work on customizations.)
- In case the customer needs our engagement, we will quote it as an R&D contract.
- If we need to appear in person, the customer will fund our travel (demonstrations, on-site troubleshooting, etc.)
  - Most of the followup work can be performed remotely.
  - The discussions can be conducted on zoom.

Hardware, Firmware, Software, and Readout

The details are negotiable.

Hardware, described in detail in these slides.

Firmware.

- We are proposing our existing firmware framework, which is tightly knit into our hardware.
- We do not expect extensive modifications.

Software.

- We are proposing our existing software framework. It is interfaced with our hardware and firmware.
- We developed extensive libraries accompanying our hardware products.
  - Low level libraries in the form of Application Programming Interfaces (API).
  - High level scripts controlling the digitizers under Jupyter.
- We expect customizing the “look and feel” to meet the needs of the customer.

Readout, described in detail in Part IV.

- We are proposing our existing readout framework. It is interfaced with our hardware and firmware.
- We developed extensive readout formats and libraries performing the readout, described in later slides.
- Readout, data collection, and data management are controlled with extensive GUIs.

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Part II: Block diagrams

- Our DAQ is modular. It consists of 5 boards which can be connected in different ways.

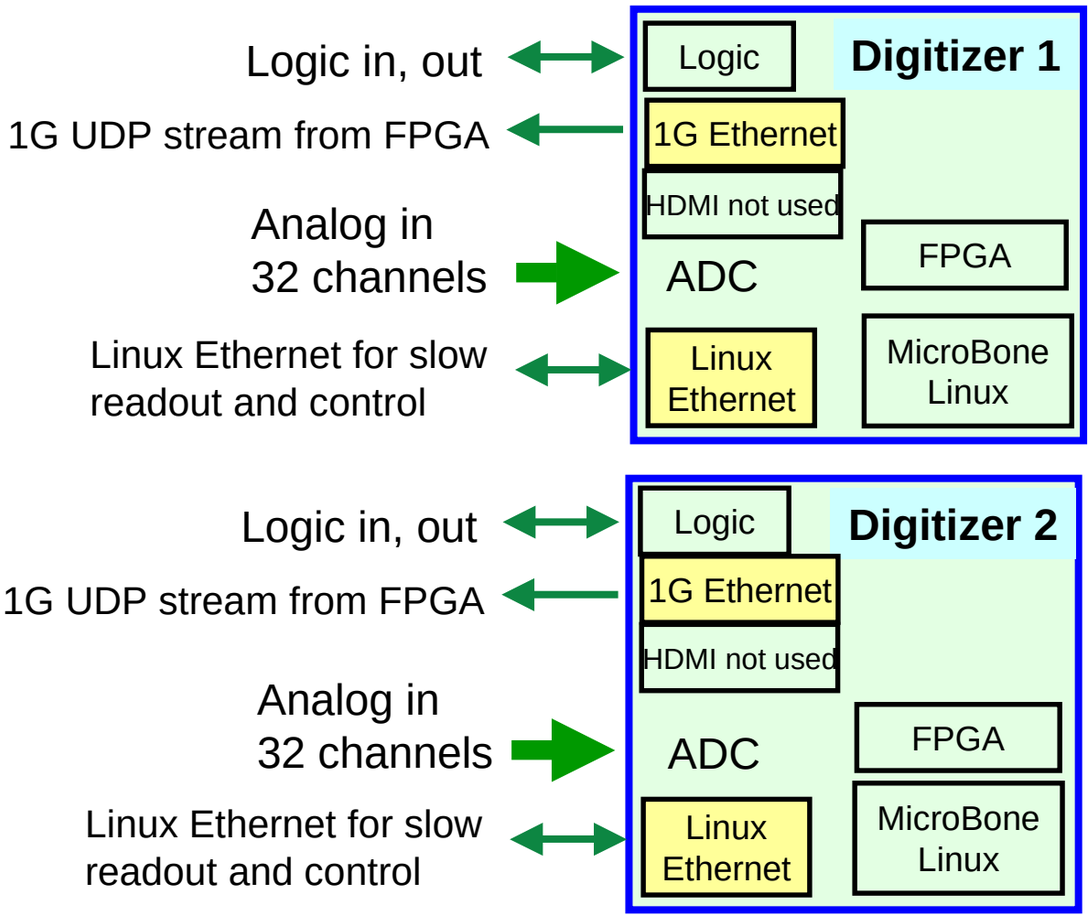
- The minimal DAQ consists of Board #1 (digitizer) + Board #5 (embedded Linux). Other boards are optional.
- In addition to the boards, we highly recommend adoption of our readout and control.
- We will show the block diagrams in order to provide a general orientation.
- Boards #1 and #2 provide two RJ45 Ethernet sockets: ~15 MB/s and 1G. The 10G board #4 is optional.

1. *Digitizer* with coax LEMO inputs, ADCs, FPGA, Embedded Linux, Ethernet, and on-board nonlinearity calibration.
   - Recommended for high precision HPGe. The board can be assembled with 14-bit or 16-bit ADC chips.
2. *Digitizer* with FERA ribbon inputs. Otherwise identical to Board 1.
   - Lower cost input connectors recommended for SiPM arrays and similar lower precision sensors.
3. *Logic Manager Module* with fast links for boards #1 and #2: triggering, event building, and clock distribution.
   - Useful when the detector needs the system-wide “events”. (E.g., cosmic flash seen in many channels at once.)
4. *Rear Transition Module* providing **10G fiber optics readout** to every board #1, #2, or #3.
5. *Embedded Linux* board named MicroBone, derived from a popular BeagleBone Black.
   - Our every board uses MicroBone for embedded control and optional slow readout at ~15 MB/s.

The **simplest** DAQ consists of just the digitizers

All channels are independent. They stream timestamped data on each individual pulse.

Independent digitizers



Control is managed by MicroBone Linux, using Ethernet

Readout can be performed with:

1. MicroBone Linux at ~15 MB/s
2. UDP Ethernet from FPGA, at **1** gigabit/s

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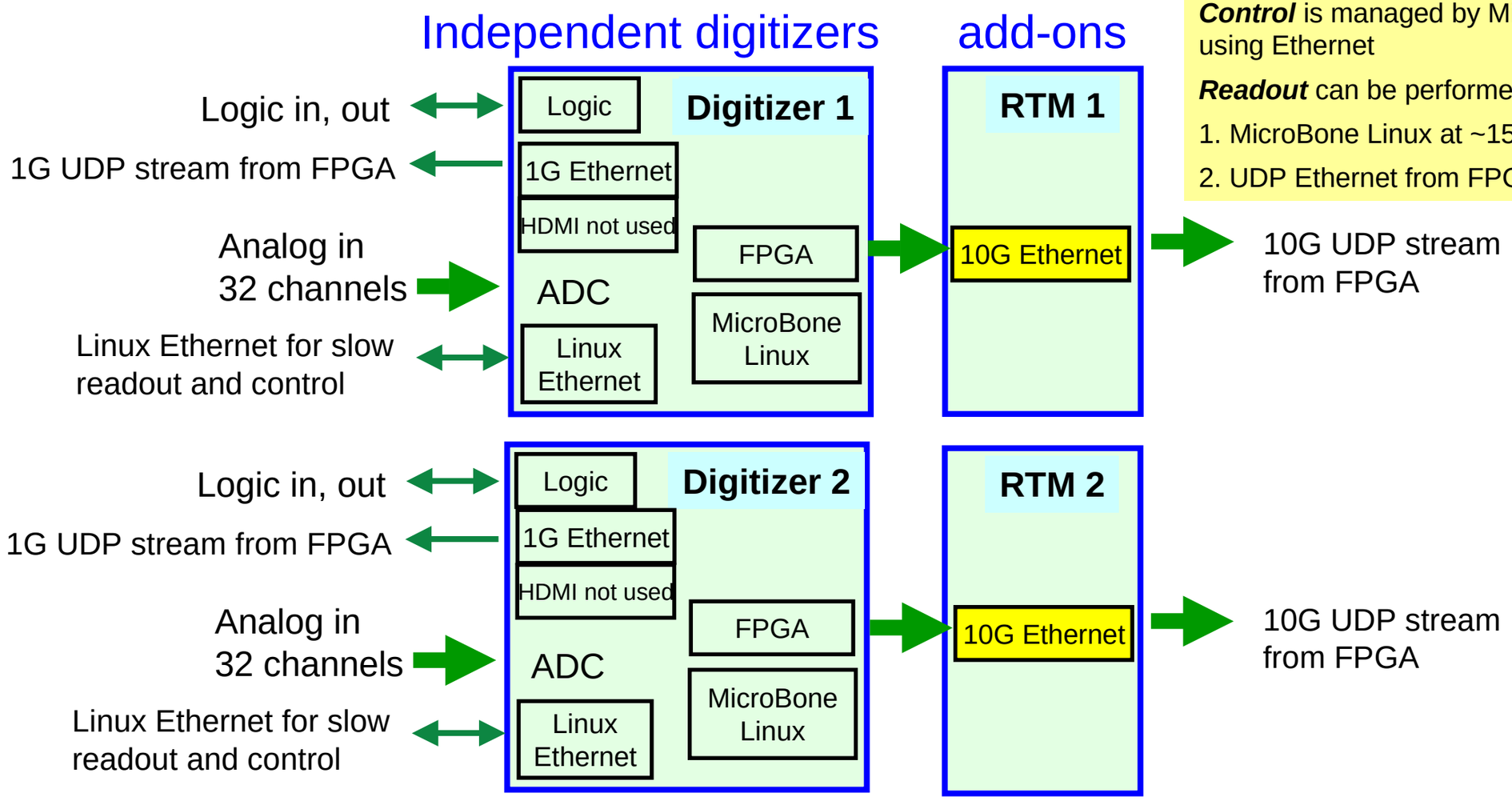
The **simple**, but **faster** DAQ is adding 10G UDP streaming

10G optical fiber is driven by the Rear Transition Module from each board



Control is managed by MicroBone Linux, using Ethernet

Readout can be performed with:

1. MicroBone Linux at ~15 MB/s
2. UDP Ethernet from FPGA, at **10** gigabit/s

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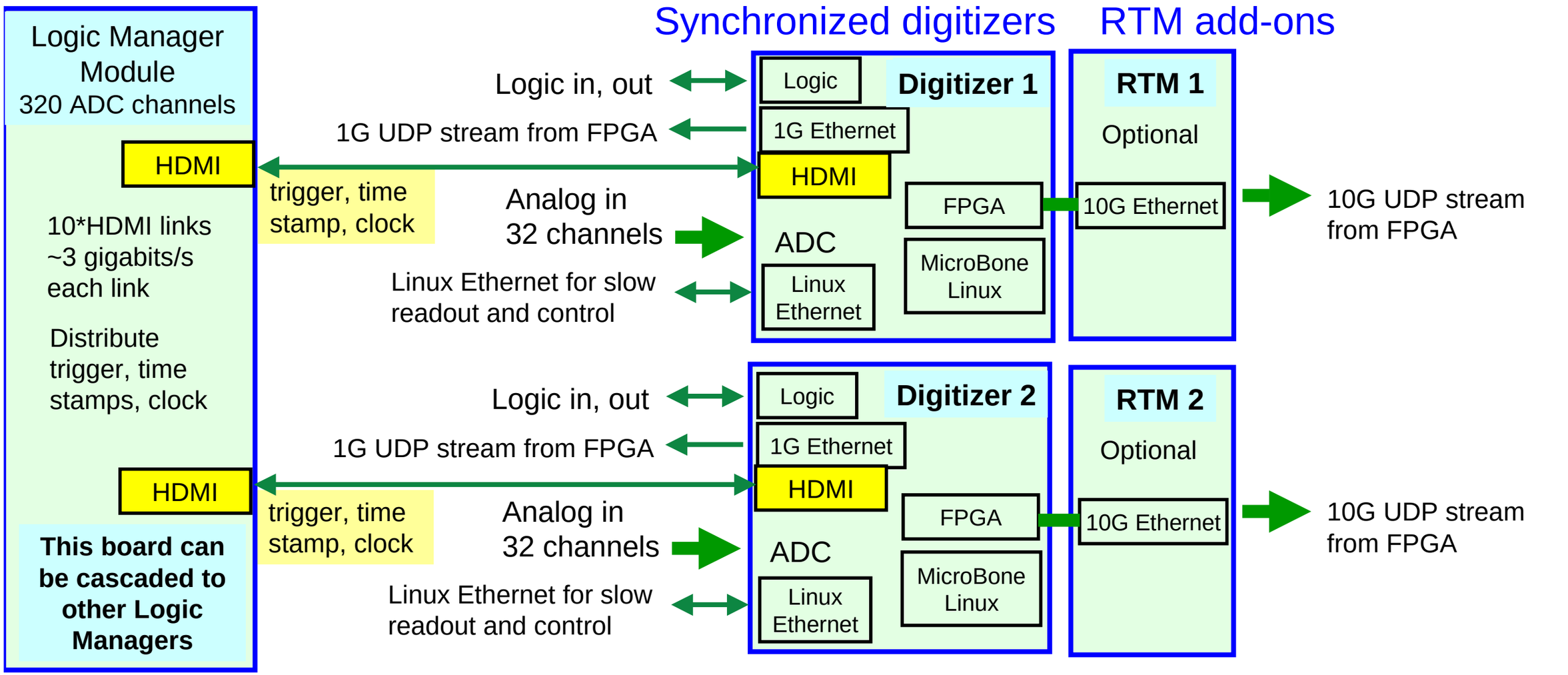
The **synchronized** DAQ is adding the Logic Manager Module

Used for coincidences, common clock, and event building



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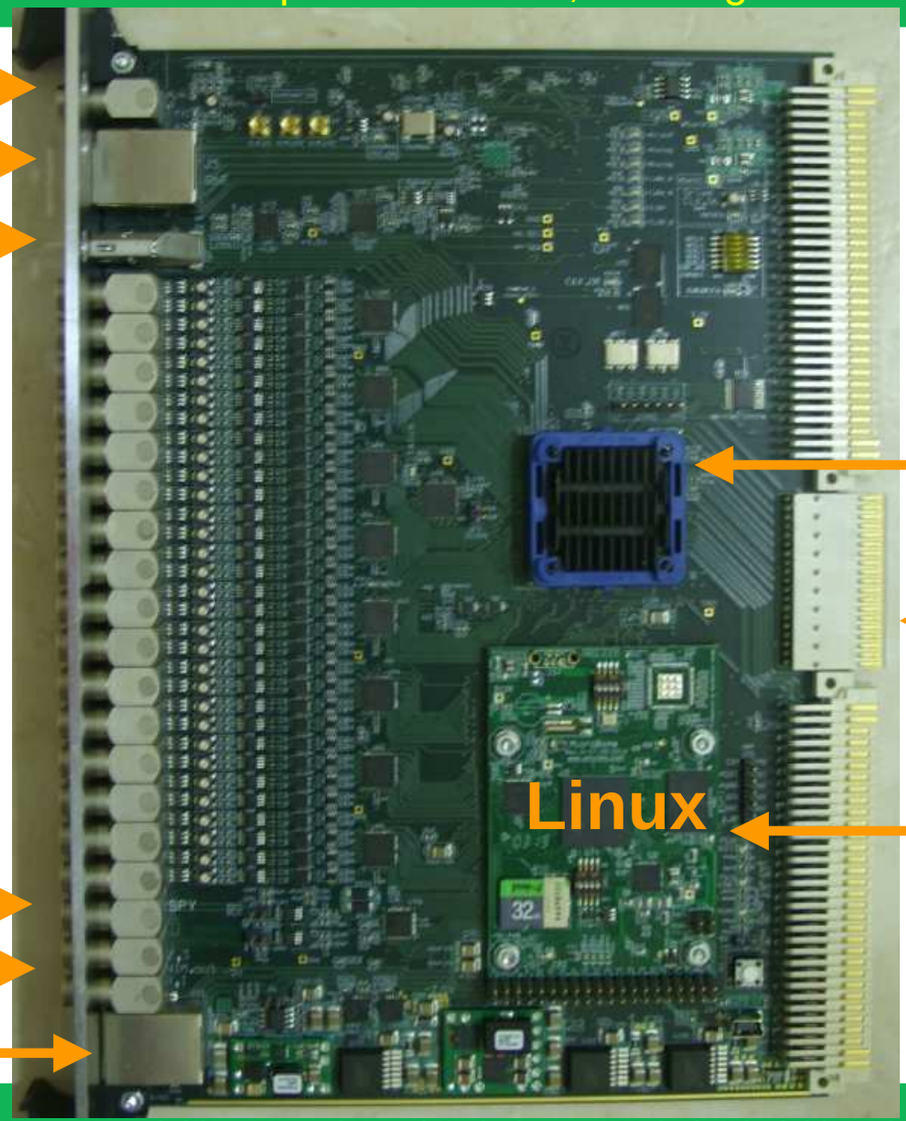
Part III: DAQ Boards Overview

- We will show photographs and describe the boards in more detail.

1. *Digitizer* with coax **LEMO** inputs, ADCs, FPGA, Embedded Linux, Ethernet, and on-board INL calibration.
   - Recommended for high precision HPGe. The board can be assembled with **14-bit** or **16-bit** ADC chips.
2. *Digitizer* with **FERA** ribbon inputs. Otherwise identical to Board #1.
   - Lower cost input connectors recommended for SiPM arrays and similar lower precision sensors.
   - Apart from the input connectors, boards #1 and #2 are internally identical.
3. *Logic Manager Module* with fast links for boards #1 and #2: triggering, event building, and clock distribution.
   - Useful when the detector needs the system-wide “events”. (E.g., cosmic flash seen in many channels at once.)
   - This board can be cascaded to other Logic Managers in order to build DAQ with thousands of channels.
4. *Embedded Linux* board named **MicroBone**, derived from BeagleBone Black.
   - Our every board uses MicroBone for embedded control and optional slow readout at ~15 MB/s.
   - Every MicroBone is running **Debian-10** Linux distribution: local storage, network storage, Python, Jupyter...
5. *Rear Transition Module* providing **10G** fiber optics readout to every board #1, #2, or #3. The RTM is optional.
   - Note that boards #1 and #2 provide two RJ45 Ethernet sockets: ~15 MB/s and 1G. The 10G board is optional.

32-Channel Digitizer With **LEMO** Inputs and On-Board Calibration

Apart from the input connectors, both digitizers are internally identical



NIM in 0,1

1G Ethernet directly to FPGA

HDMI link

High quality coax inputs with pseudo-differential LEMO connectors

Channels 0..31
14-bit or 16-bit ADC's

Analog out 0,1

NIM out 0..3

Linux Ethernet

- On - board calibration with 16-bit voltage DAC

Apart from the input connectors, both digitizers are internally identical

FPGA XC7K410T
with 3,180 kilobytes of RAM

High speed Hard Metric P0

MicroBone
Single Board Computer (SBC)
Derived from BeagleBone Black
Running Linux

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32-Channel Digitizer With **FERA** Inputs and On-Board Calibration

FERA inputs are single-ended: gnd, signal 1, gnd, signal 2, etc

NIM in 0,1

1G Ethernet directly to FPGA

HDMI link

Serial UART

Channels 0..15

Bias voltage and +5V for channels 0..15

SiPM bias voltage is optional

Channels 16..31

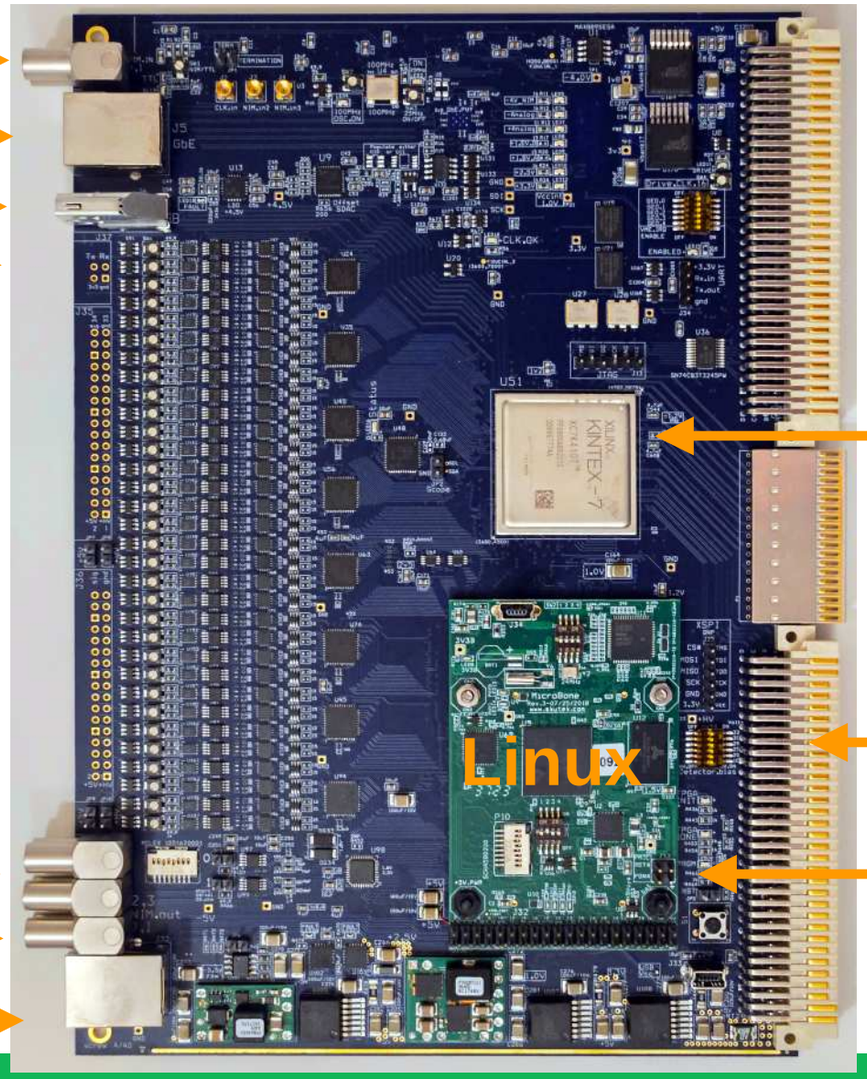
Bias voltage and +5V for channels 16..31

FERA inputs are single-ended:
gnd, signal 1
gnd, signal 2
gnd, signal 3
…

Analog out 0,1

NIM out 0..3

Linux Ethernet



- On - board calibration with 16-bit voltage DAC

Apart from the input connectors, both digitizers are internally identical

FPGA XC7K410T
with 3,180 kilobytes of RAM

High speed Hard Metric P0

Optional SiPM bias voltage in 6 steps 10..32 volts

MicroBone
Single Board Computer (SBC)
Derived from BeagleBone Black
Running Linux

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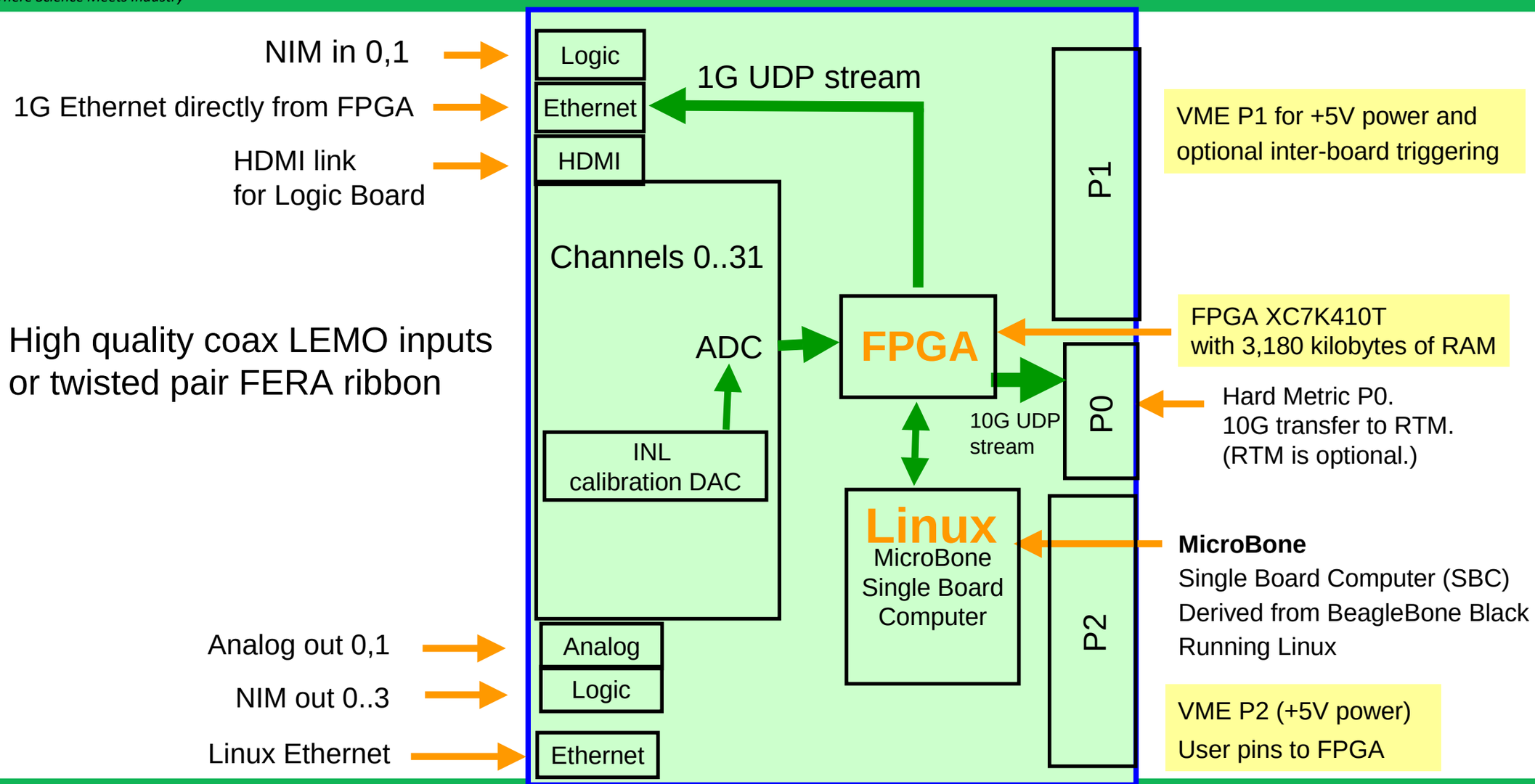
Block Diagram: 32-Channel **Digitizer** With On-Board Calibration

Boards with the FERA input and Coax input are internally identical



Logic Manager Module for Large DAQ

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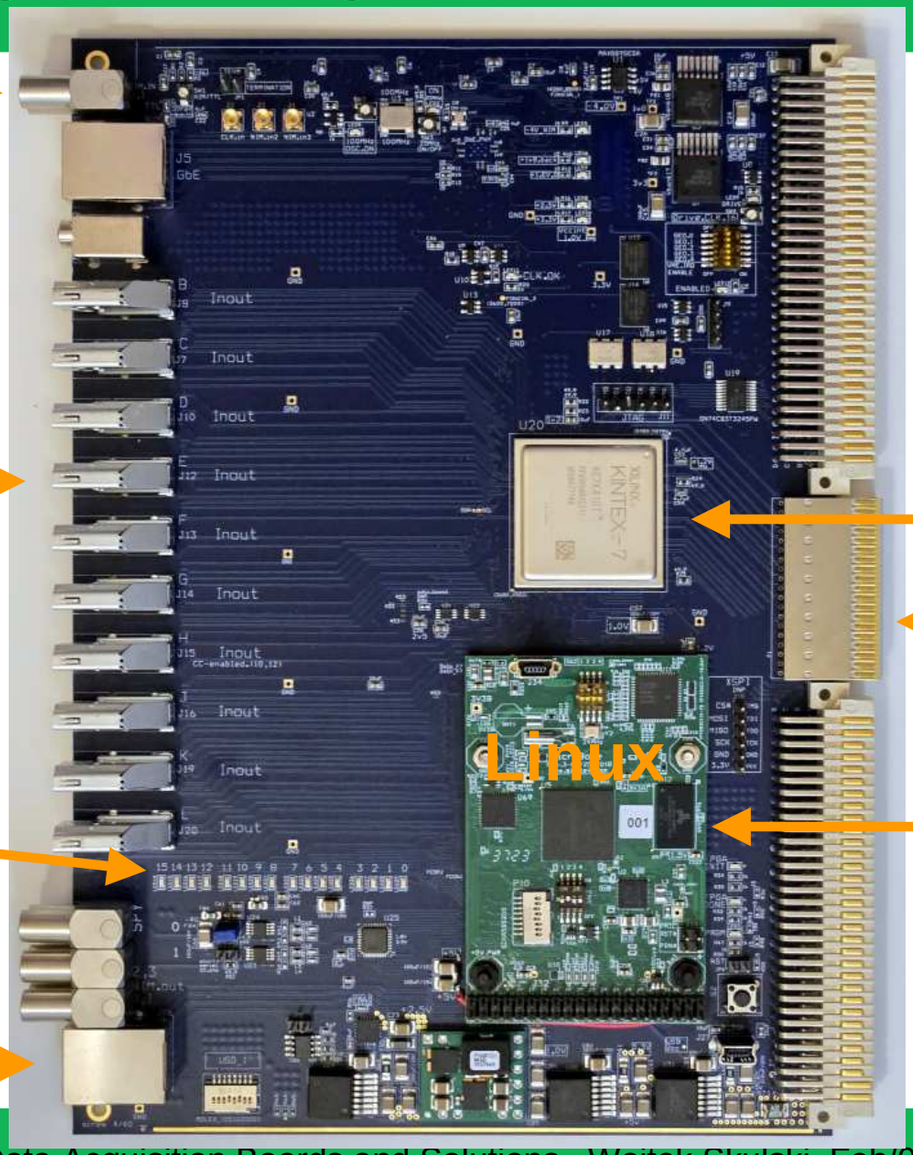


NIM in 0,1

1G Ethernet

Serial UART

HDMI links 0..9
to Digitizer slaves

16*LED for
diagnostics

Analog out 0,1

NIM out 0..3

Linux Ethernet

- **Logic & Trigger Master**

When to use this board:

You need a common clock.

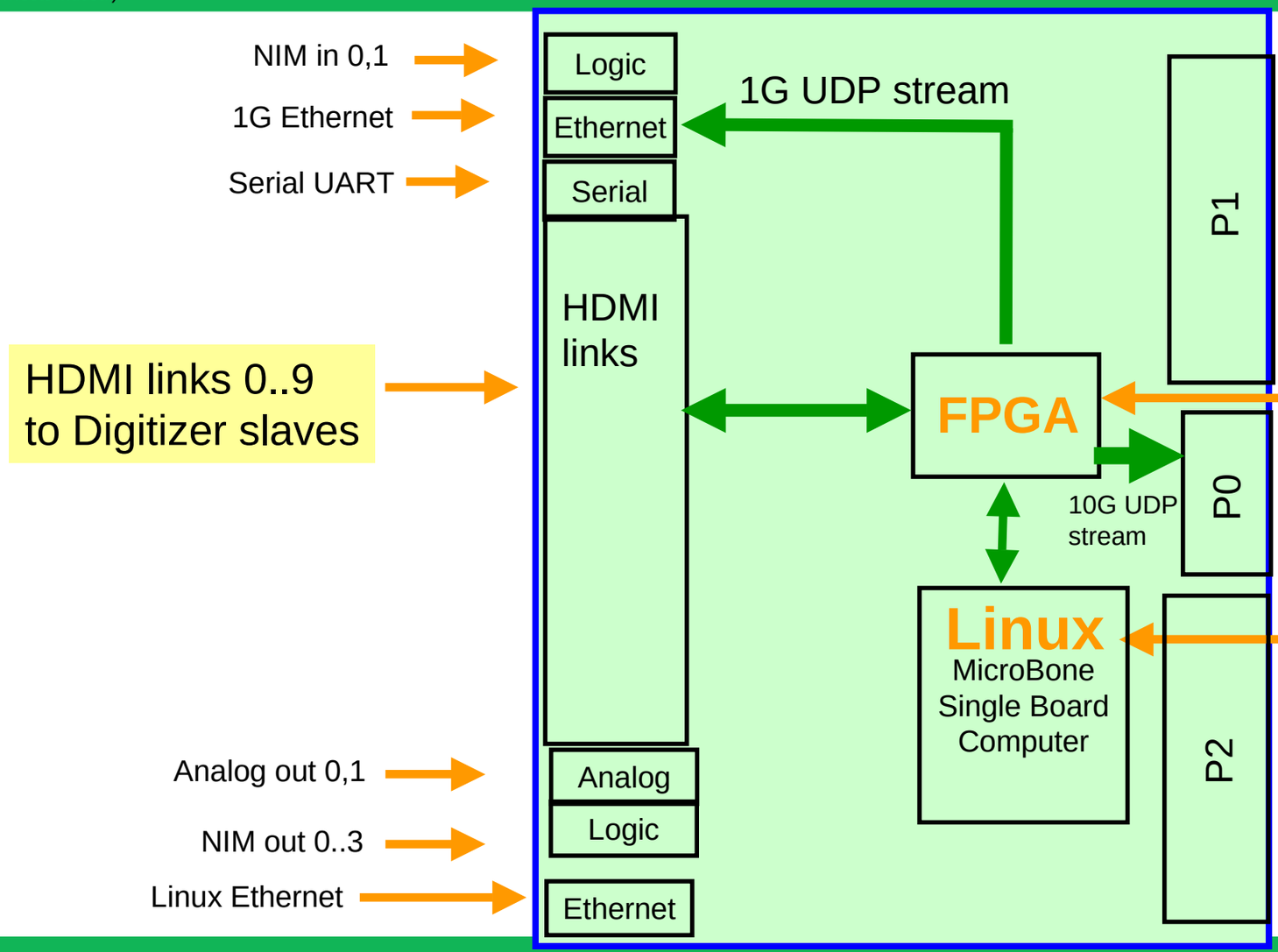
You need a complex trigger.

FPGA XC7K410T
with 3,180 kilobytes of RAM

Hard Metric P0

MicroBone
Single Board Computer (SBC)
Derived from BeagleBone Black
Running Linux

Block Diagram: Logic Manager Module for Large DAQ



- **Logic & Trigger Master**

When to use this board:

You need a common clock.

You need a complex trigger.

VME P1 for +5V power and optional inter-board triggering

FPGA XC7K410T with 3,180 kilobytes of RAM

Hard Metric P0.
10G transfer to RTM.
(RTM is optional.)

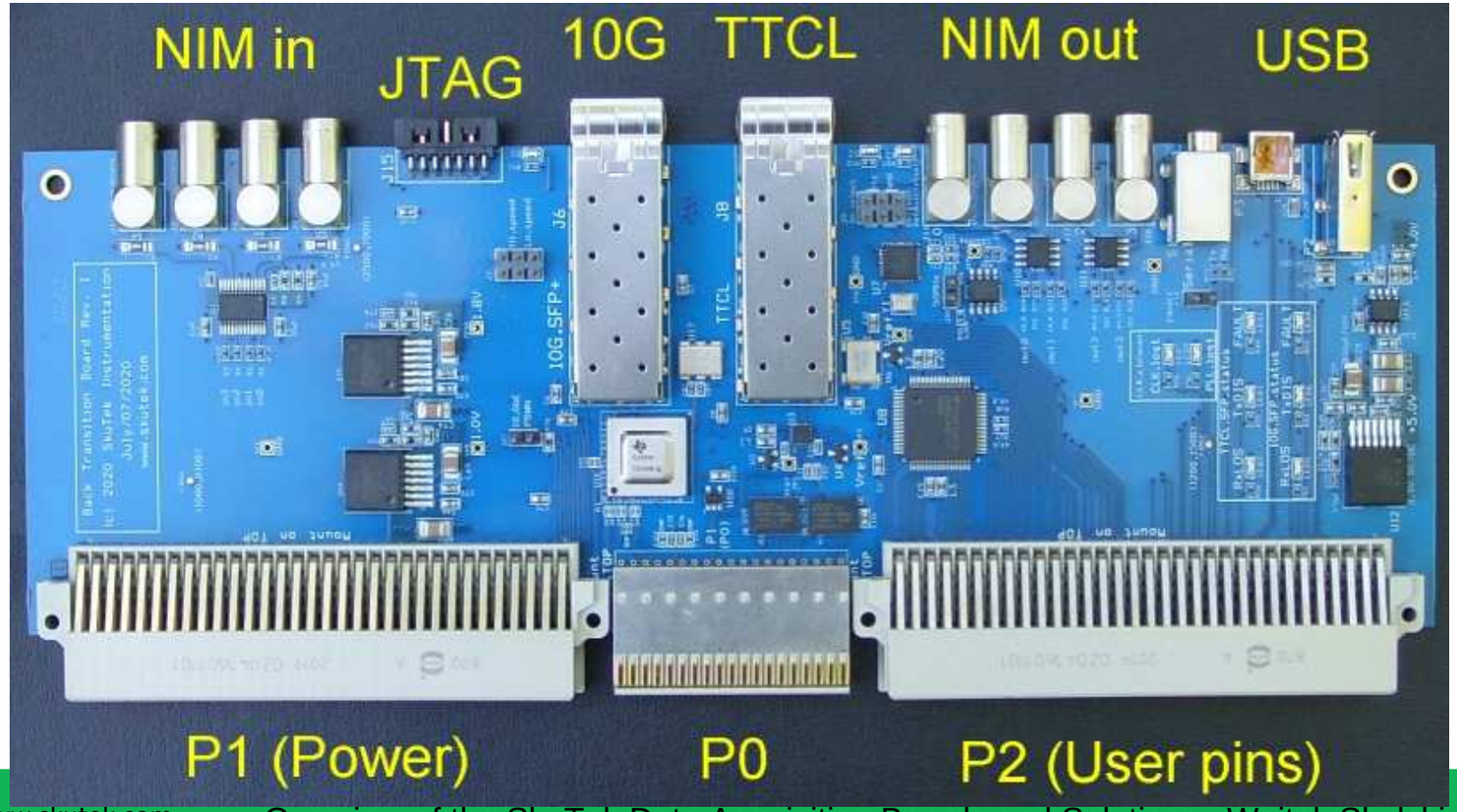
MicroBone
Single Board Computer (SBC)
Derived from BeagleBone Black
Running Linux

VME P2 (+5V power)
User pins to FPGA

High Speed 10G Streaming Rear Transition Module (RTM)

Needed if you want to offload events at 10G from each board

- Rear Transition Module (RTM) will help with system integration with Nuclear Physics framework.
- High speed 10G data streaming with GRETA-compatible binary format.
- White Rabbit (WR) support is under development (already tested at FRIB).



- **Optional Streaming RTM**.

Can be added to any our board.

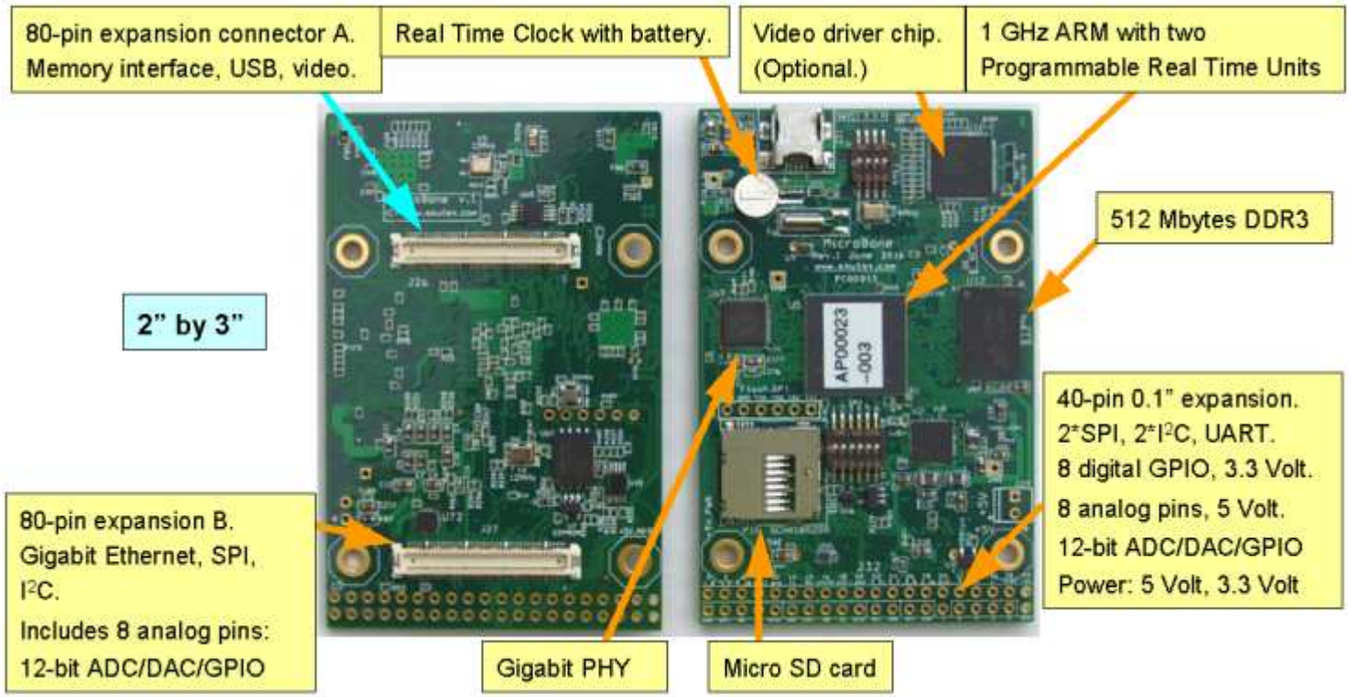
When to use:

You need 10G streaming output from every board.

Embedded Control Is BeagleBone Black Compatible

BBB is a very popular open hardware alternative to Rpi

- Local Linux Single Board Computer is embedded with every SkuTek module:
  - Our Linux SBC was derived from, and it is highly compatible with BeagleBone Black.
  - MicroBone is our own clone of BeagleBone Black.
  - We developed it because other such boards (like Rpi) cannot be cloned due to proprietary design. BBB could and we did it.
  - The original BBB could not be embedded due to its many connectors. We moved all pins to the 80-pin expansion sockets.
  - MicroBone is running a version of Linux derived from BeagleBone Black.



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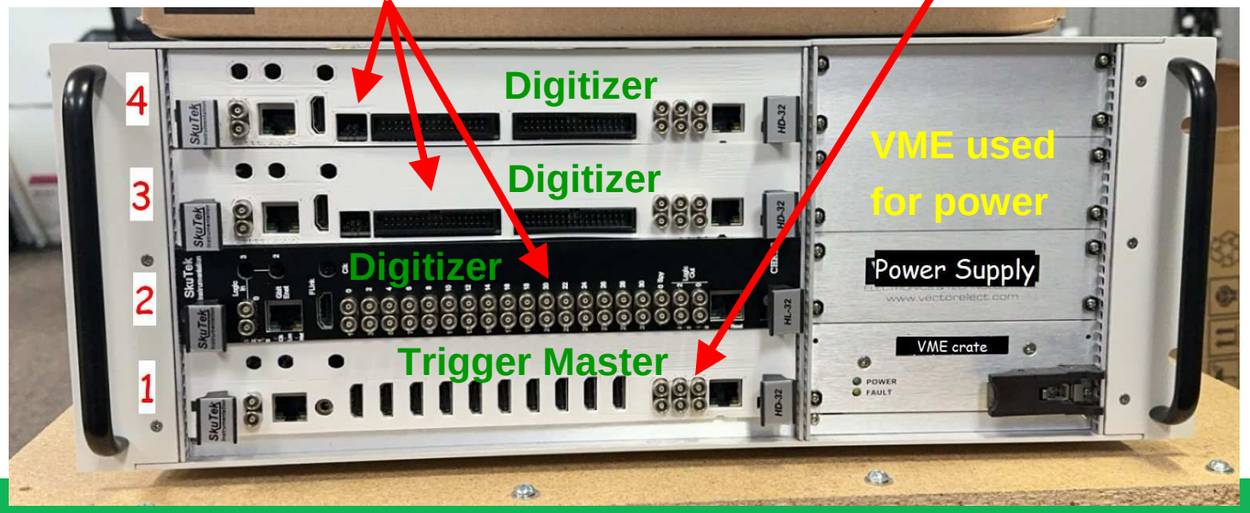
Demo of High Channel Density Digital DAQ

The modular DAQ can grow in the future.

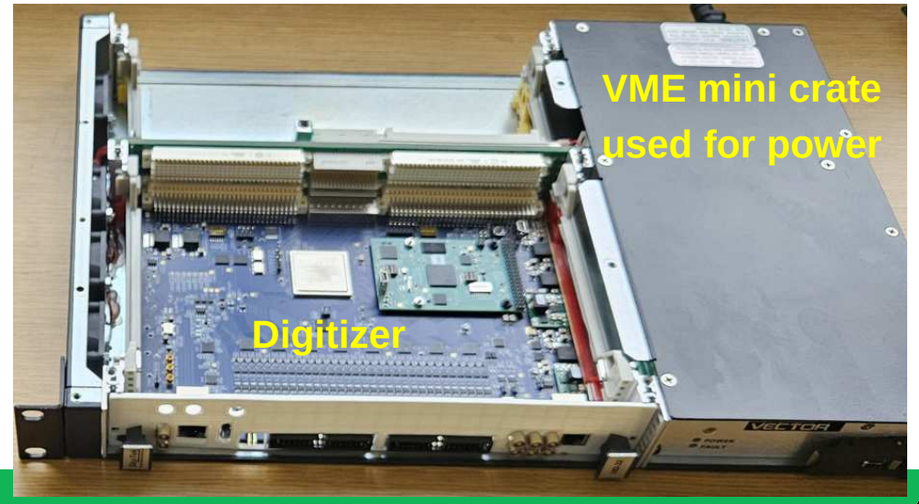
- We are offering a digital DAQ with practically unlimited number of channels, added in multiple of 32. (Think thousands…)
- Our digitizers can work triggerless. As soon as a pulse is detected in any channel, that channel is streamed out via Ethernet.
- **Or**, the system-wide trigger is worked out by cascaded Trigger Logic Master boards handling system-wide hit patterns.
- Both our present and future digitizers will be fully compatible with this DAQ architecture.

1. *32-channel digitizer* with **LEMO** inputs for high resolution detectors.
2. *32-channel digitizer* with **FERA** inputs suggested by ANL for silicon strips, scintillators, or SiPM detectors.
3. *Cascadable Trigger Master* serving up to 10 digitizers (up to 320 channels). Can be cascaded for thousands of channels.

Multi **digitizer** configuration with **Trigger Master**.



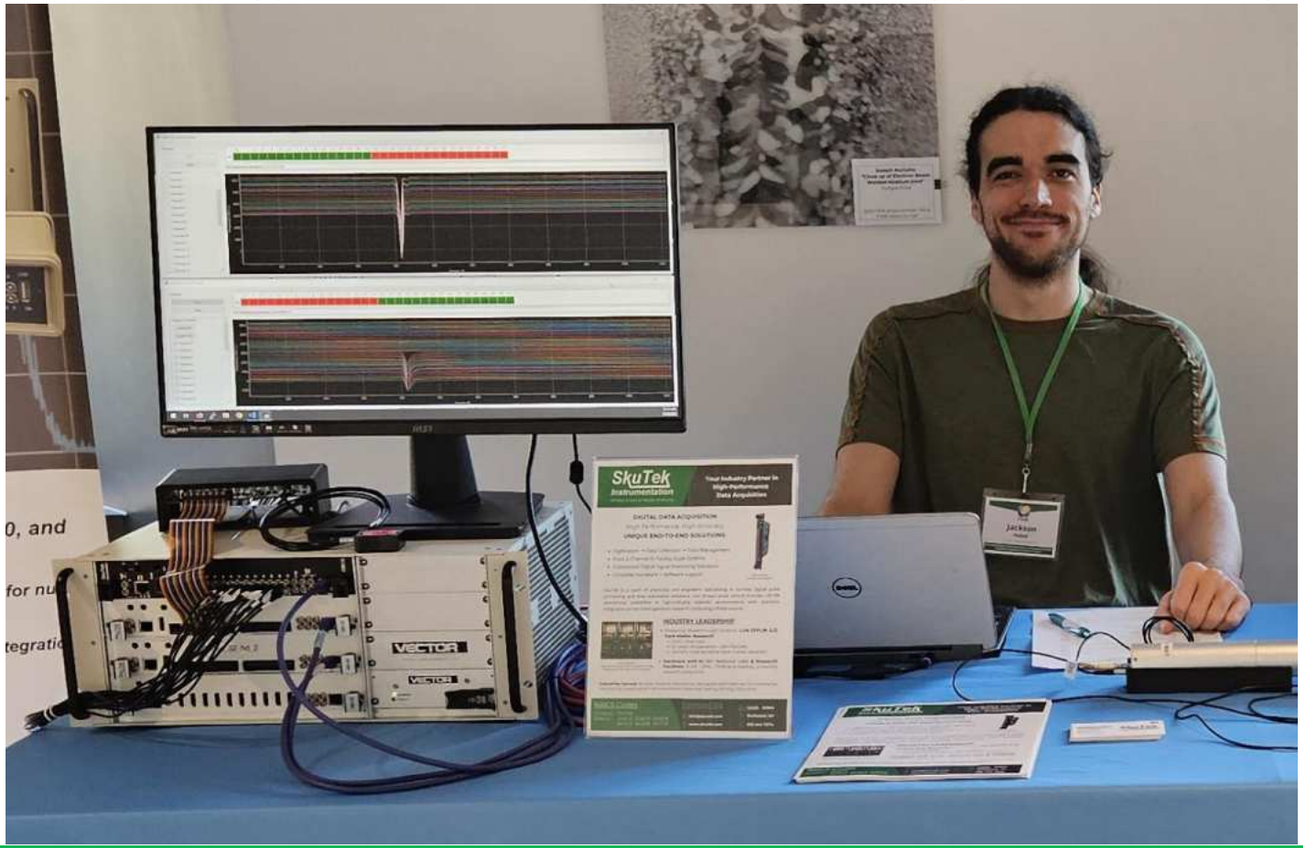
Single digitizer configuration.



Demo: High Channel Density Digital DAQ

DAQ demo presented at FRIB DAQ workshop in October 2025 (96 channels).

1. *32-channel digitizer* with **LEMO** inputs for high resolution detectors.
2. *32-channel digitizer* with **FERA** inputs suggested by ANL for silicon strips, scintillators, or SiPM detectors.
3. *Cascadable Trigger Master* serving up to 10 digitizers (up to 320 channels). Can be cascaded for thousands of channels.



SkuTek Engineer Mr. Jackson Hebel showcasing our sample DAQ at FRIB, October 2025.

Performance

In the next few slides we are documenting the performance of our solutions.

Low Noise and Excellent Pulse Response

Crucial for high quality data!

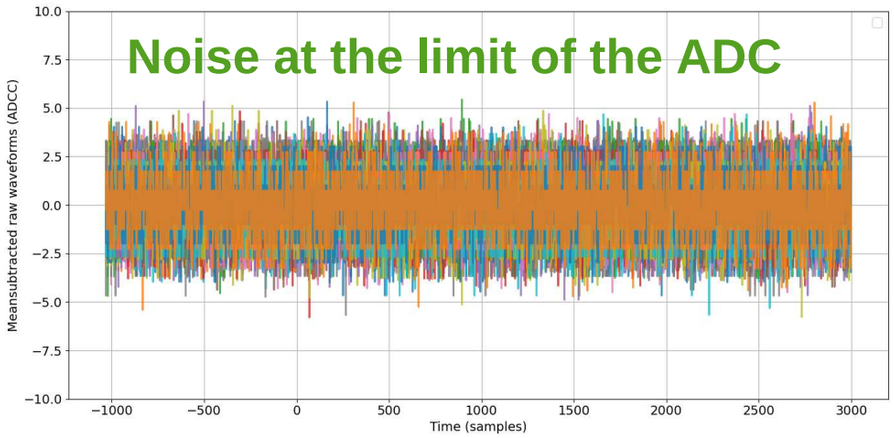
- Signal range = 2 volts, digitized with 14 bits @ 100 MSPS.
- 16-bit version of the ADC chip is available. We can use it.

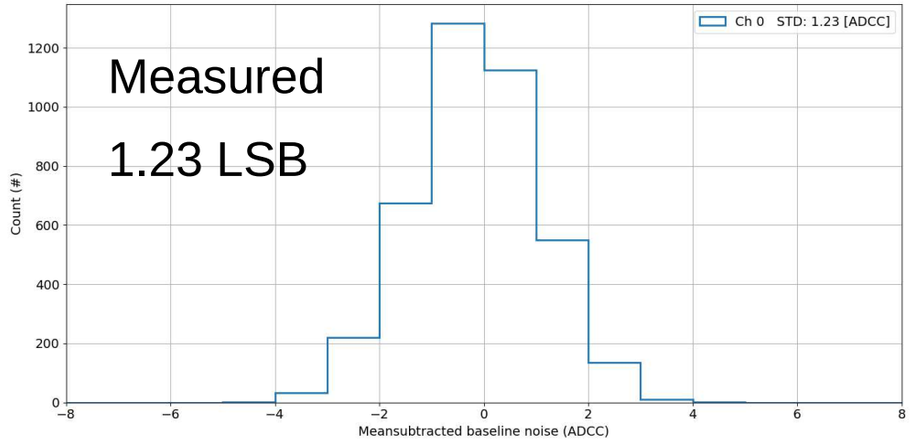
ADC noise RMS = **1 LSB** from the datasheet

Noise RMS = **1.23** LSB = 150 µV

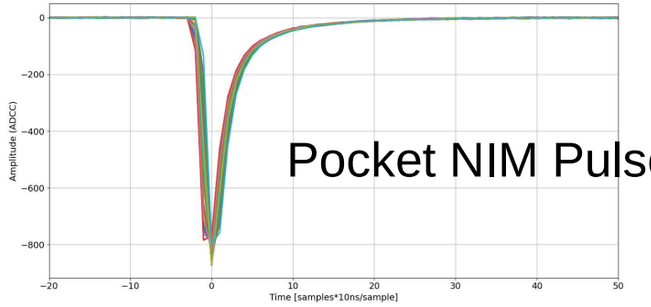
1 LSB = 2 V / 16k = 122 µV

Noise waveforms from all 32 channels





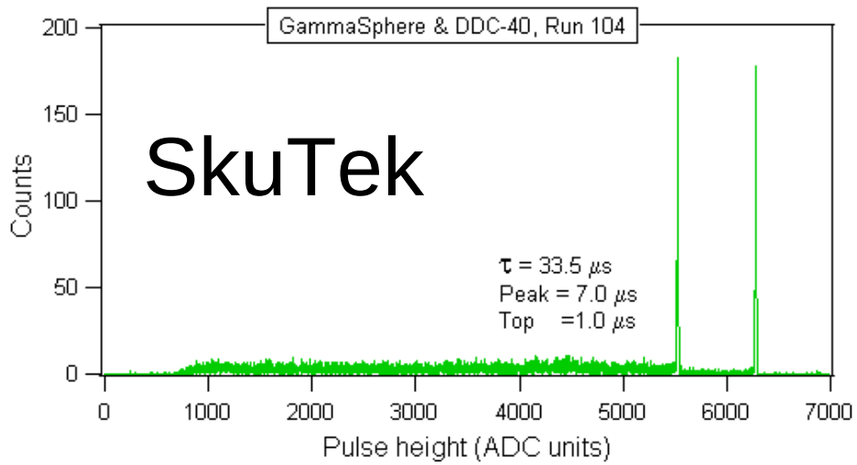
Channel-channel timing resolution ~100 ps



Pocket NIM Pulser (~10 ns pulse, similar to PMT)

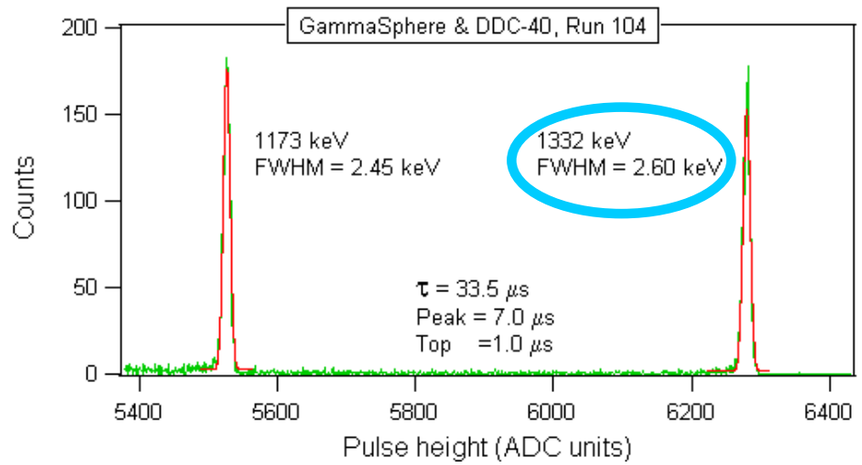
Apple-to-Apple Comparison of the LBNL and SkuTek Digitizers

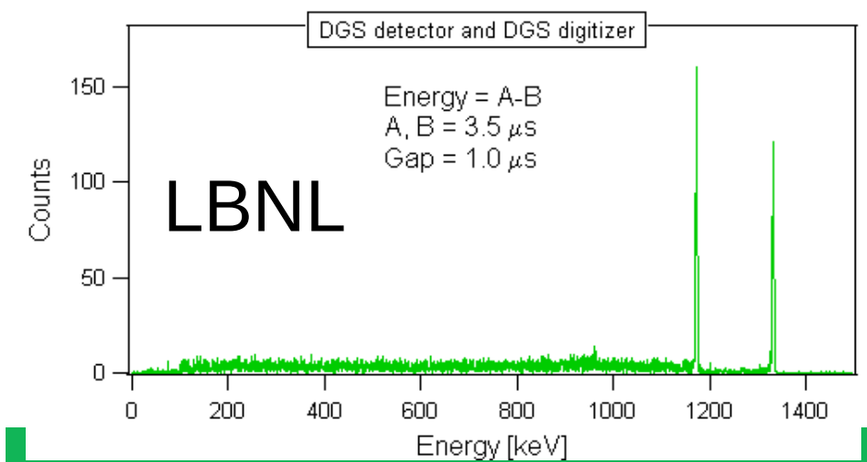
- We **compared** ^{60}Co spectra obtained with Gammasphere detectors with LBNL and SkuTek digitizers, using the *same events*.
- Our digitizer achieved a SQRT(2) better resolution than the LBNL digitizer, because we applied 2 * *longer running sums*.



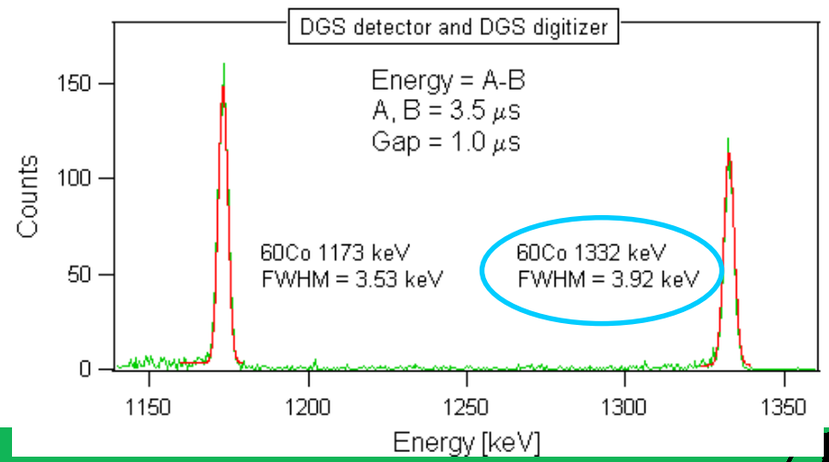
SkuTek
1173 -> 2.45 keV
1332 -> 2.60 keV

Better by SQRT(2)





LBNL
1173 -> 3.53 keV
1332 -> 3.92 keV



Part IV
Readout.
How are we offloading the data?

With a system of this complexity, development of control and readout can take literally years. We have already done most of the work. We are offering tools and solutions which can be configured for a particular customer or experiment.

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Event Streaming With 1G Copper Or 10G Optical Ethernet.

Each digitizer can generate its own 1G or 10G event stream

32-Channel Self-Triggered Digitizer

Rear Transition Module (RTM)

White Rabbit clock will be added to the system

From each board

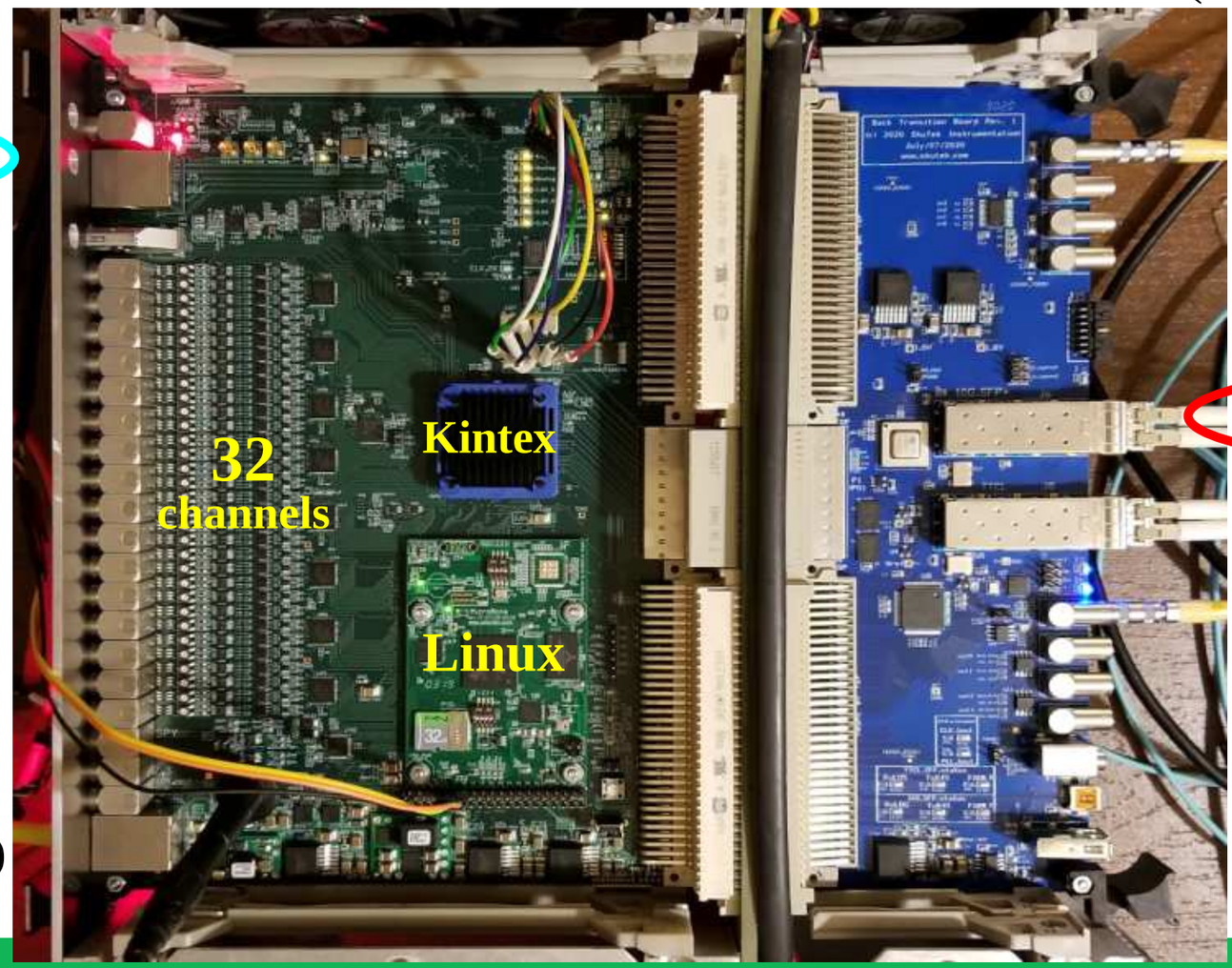
1 GbE (from FPGA)

LVDS link

32 Analog inputs

2 Analog outputs

1 GbE (Linux)



4 * NIM in

From each board

10 G Ethernet (from FPGA)

Optical TTCL

Compatible with GRETA

4 * NIM out

Serial UART (Linux)

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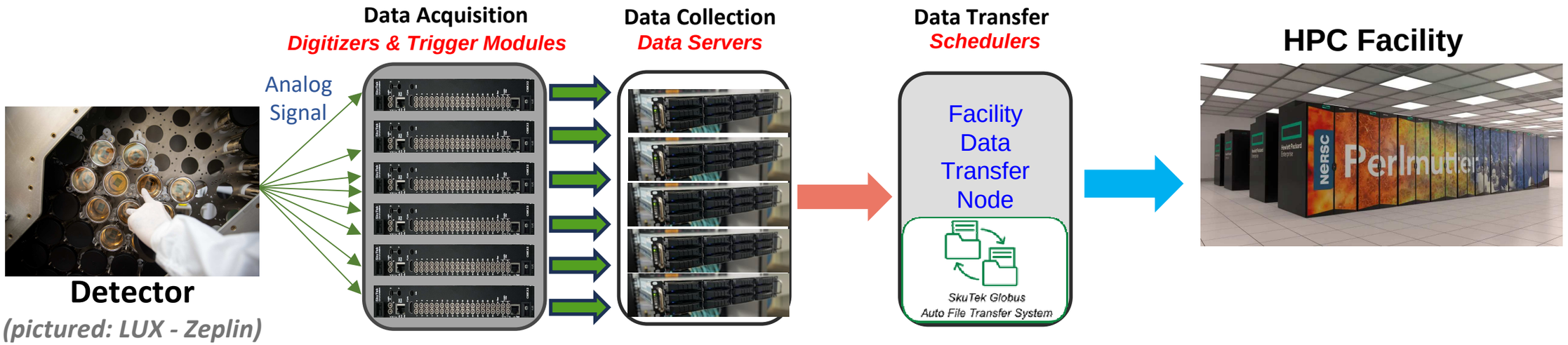
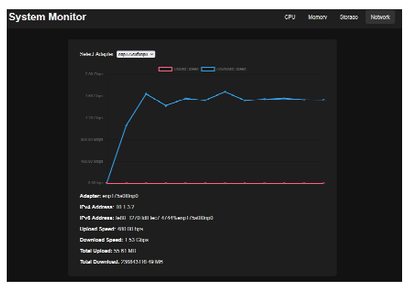
Complete End-To-End DAQ Solution

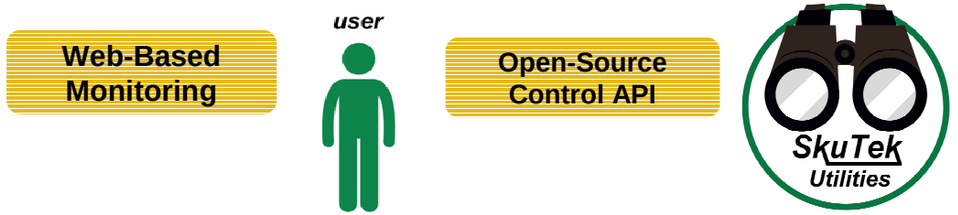
Event Streams are offloaded, managed, and directed to HPC centers (TESTED!)

- We offer hardware and software for **every stage** between the detector and HPC centers.
- The solution is scalable. Start with 32 channels, and gradually upgrade to thousands.





We offer Open Source Software



Developed under DE-SC0021502
with Jeffrey Maggio as Principal Investigator

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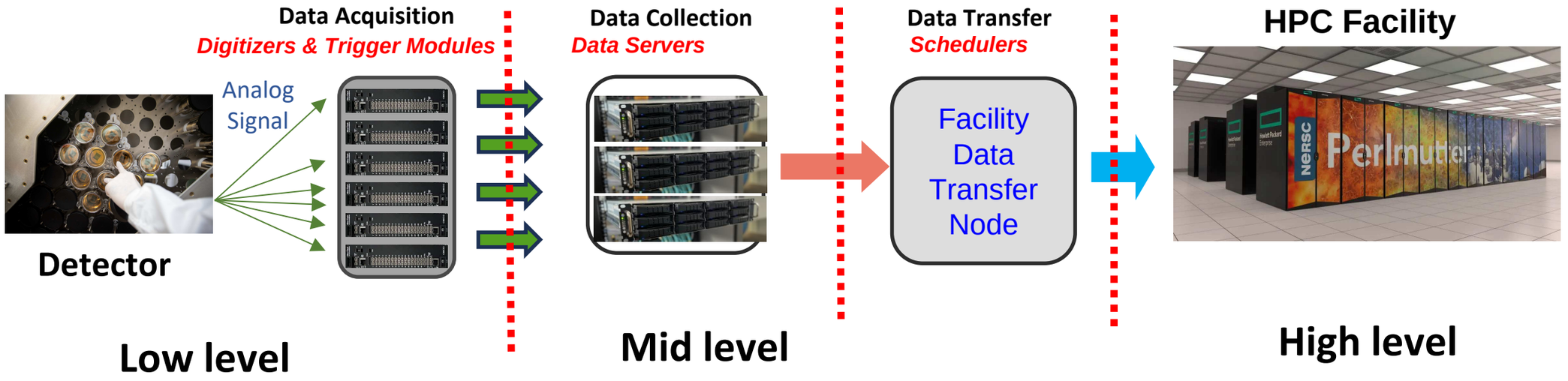
How To Integrate SkuTek DAQ With Other DAQ's

There are at least three ways to integrate multiple DAQ systems



A. Connect **logic signals** among DAQ systems: clock, trigger, busy, veto, start, stop, time stamp reset.

We provide NIM IO's.

B. Synchronize the DAQ's, **using event streams (UDP)**.

Direct data streams locally to **Data Collection Computers** (we provide) and merge with other DAQ data streams or files, using time stamps.

C. Transfer data files to HPC, using Data Collection computers and **Data Transfer Software** (we provide) and merge with other DAQ data files, using HPC computing power.

Developed under DE-SC0021502
with Jeffrey Maggio as Principal Investigator

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DAQ System **Emulation** With Simulated Streams

Crucial when you are developing a large scale networked DAQ

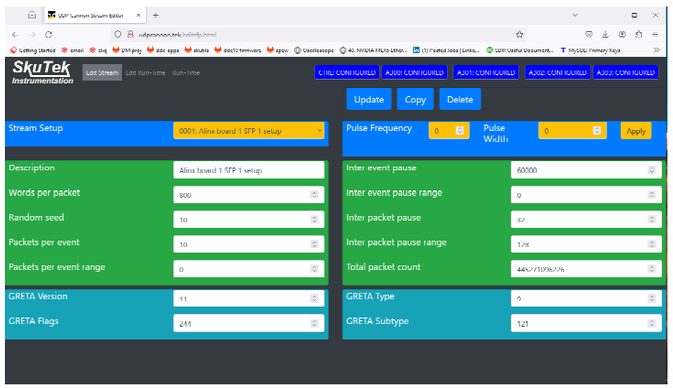
Developed under DE-SC0021502 with Jeffrey Maggio as Principal Investigator

Solidago UDP Cannon

- Helps to bring up the DAQ prior to having all digitizers in place
- Emulates data streams from 16 digitizers (512 channels)
- 0-160 Gbps programmable streaming rate (up to 20 GBytes/s)
- Realistic event structure and timing
- GRETA packet formats
- Controlled via a web Interface and REST API

Available!

- Streams can be synchronized with each other (or run independently)
- The pattern of each stream is programmable and randomizable
- It will help moving forward while the actual DAQ is being built



DAQ Control Software

Crucial for setting up and running the DAQ

- We are offering a *software control framework* based on the REST interface.
  - It currently works with our DAQ.
  - It can be ported to FRIBDAQ, Legend, or any other control software.
- Hardware Abstraction Layer (HAL) translates between control commands and FPGA registers.
  - We are offering a library of low level HAL functions.
- We developed programmatic control of the firmware (not through a graphical interface).
  - **Requested by FRIB**.
  - We are offering C utilities, Python scripts, and Jupyter codes.
  - We released remote control Python library to the public.
- ***Status***: We use it all the time to control the digitizers.

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DAQ Summary

- **Premium features of SkuTek DAQ**.
  - **High quality, low noise,** and excellent **pulse response**
  - ADC **nonlinearity** measurement and **correction**
- **High channel density DAQ** scalable from 32 channels up to thousands. Example: LZ DAQ.
  - The complete DAQ covers **all the way** from detectors to the HPC centers.
  - DAQ consists of digitizers, logic units, data collection computers, and data stream management software.
- You will receive a **complete DAQ** including optional Data Collectors.
- Option 1: 80 Gbps data collector for larger DAQ systems
- Option 2: 10 Gbps data collector for smaller DAQ systems
- FPGA-based “UDP Cannon” for stress testing the DAQ networks
- **Software**:
  - Data management, high performance file writing, Globus file transfer, SkuTek utilities.

American Made
Premium Quality
R&D funded by the DOE
Office of Nuclear Physics

Extra Slides: Education and Table Top

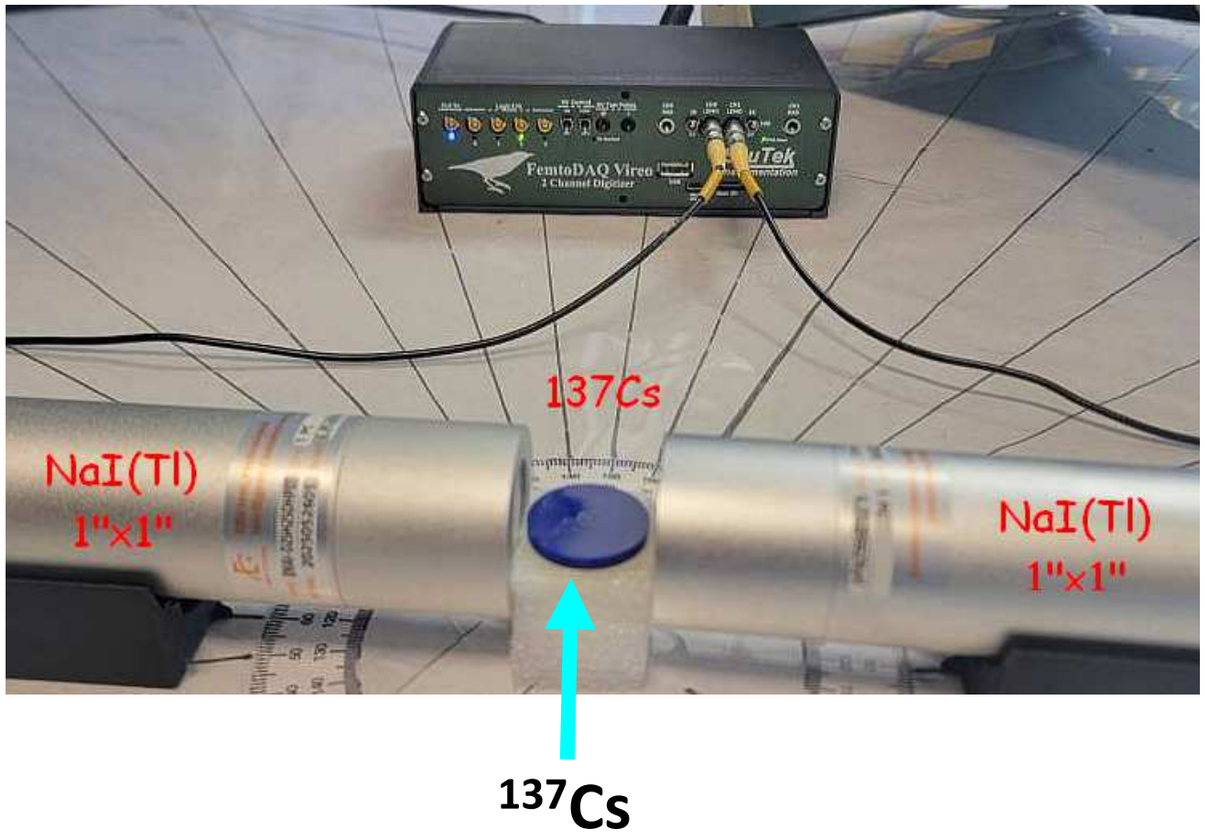
Education: Real Time Coincidence Demonstrates Compton Scattering

- **Our company has a strong commitment to education and outreach**.
- We developed a **2-channel** table-top Digitizer and Multi-Channel Analyzer (MCA) for education and student labs.
- The channels can operate in the independent mode or in coincidence mode.
- The coincidences are served in firmware. The NIM electronics is not needed.
  - Coincidence mode can demonstrate important Nuclear Physics phenomena, like Compton scattering.
- This digitizer is now used at University of Rochester, Temple University, Montclair University, and FRIB.
- The list of users is growing.
- We will demonstrate Compton scattering of the 137Cs gamma ray with two NaI(Tl) detectors.

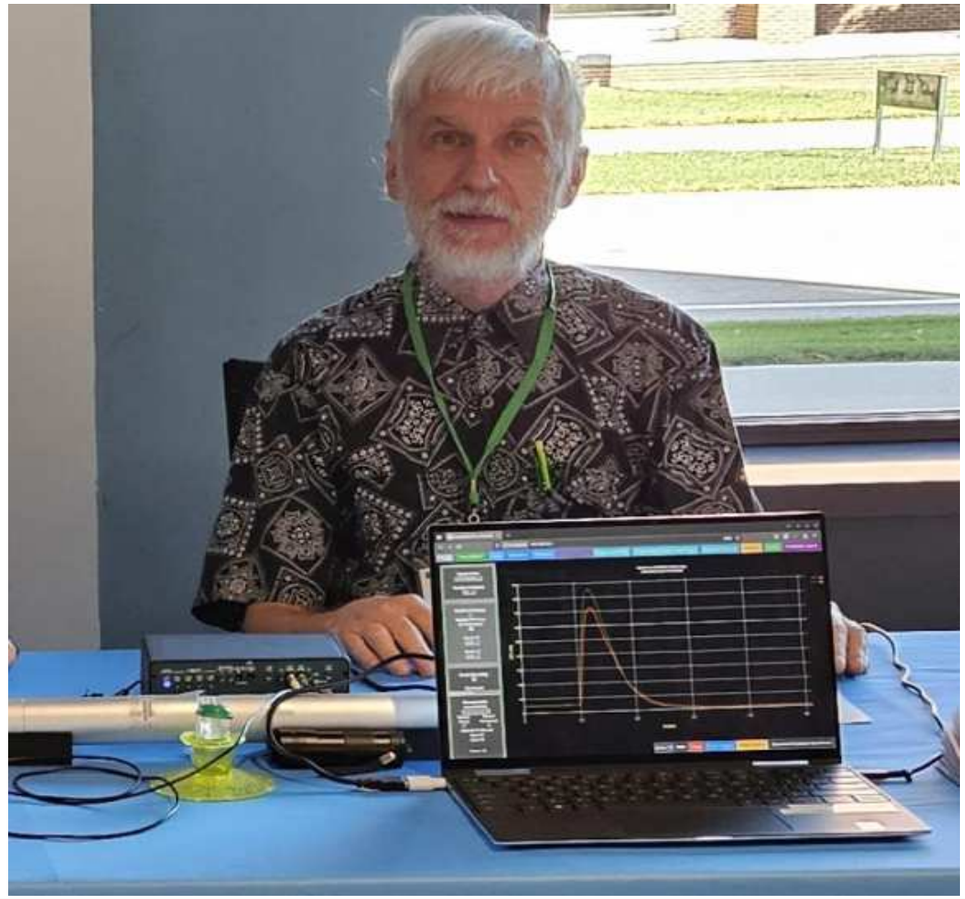
Education: Real Time Coincidence Demonstrates Compton Scattering

Table-top experiment using our 2-channel Digitizer & Multi Channel Analyzer

2-channel table-top digitizer

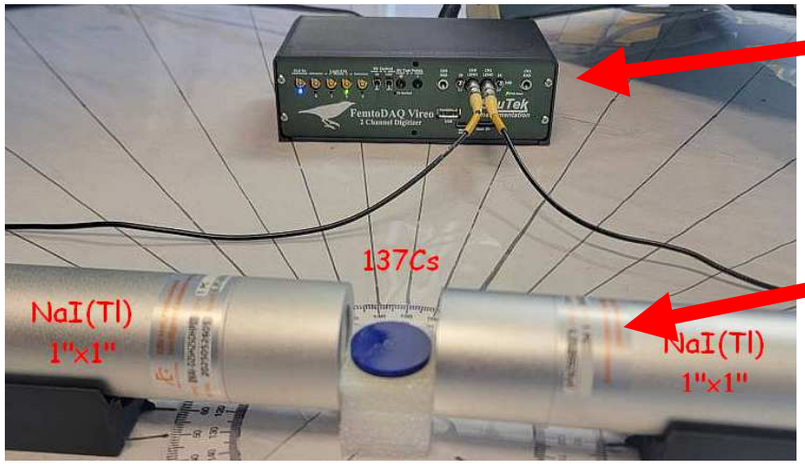


User interface demo shown @ FRIB

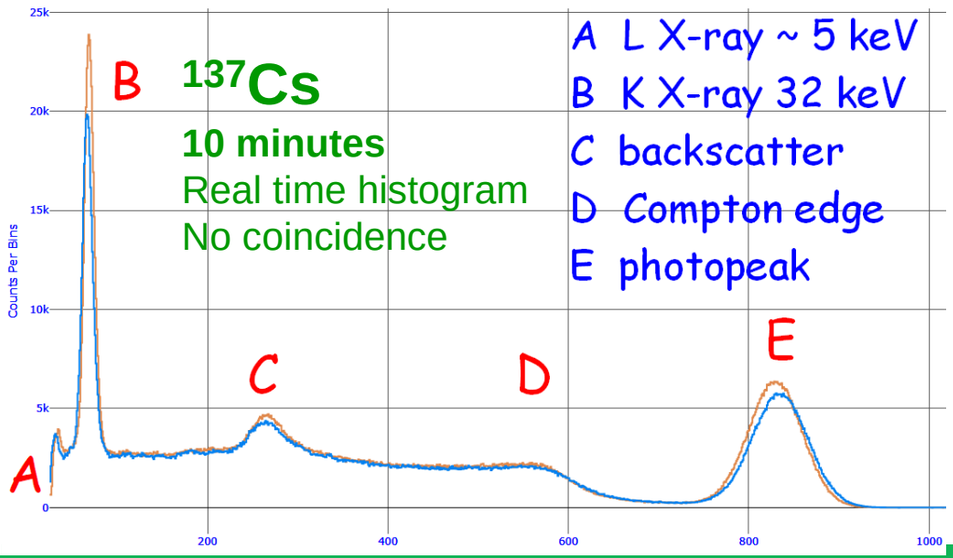


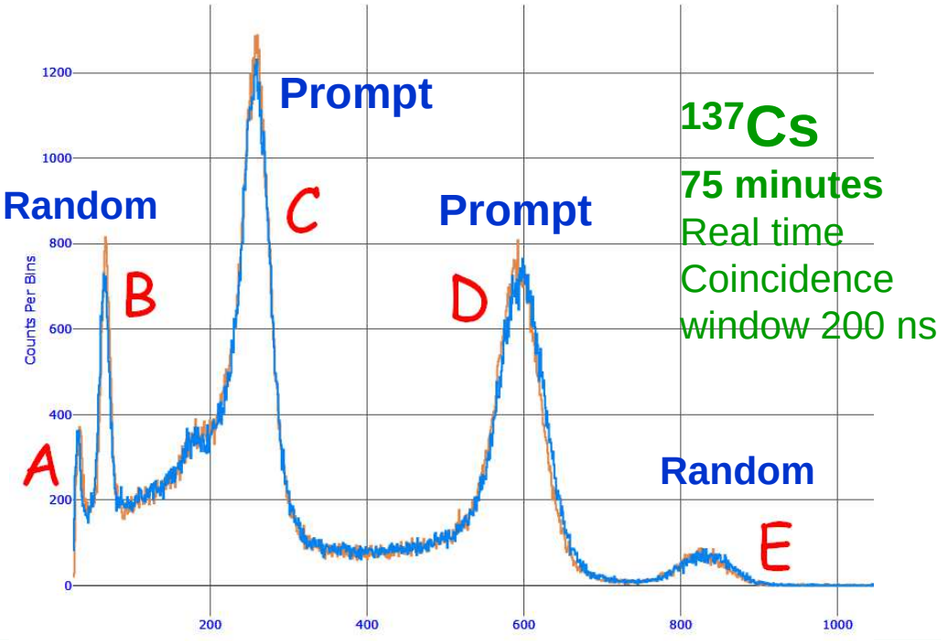
Education: Real Time Coincidence Demonstrates Compton Scattering

Table-top experiment using our 2-channel Digitizer & Multi Channel Analyzer



- 2-channel Vireo, 14 bits @ 100 MHz, on-board Linux
- Provides both an **MCA** and a **full digitizer** recording event files
- On-board coincidence firmware. NIM not needed!
- Two detectors, NaI(Tl) 1”x1”
- **Real time coincidence** with ^{137}Cs, 5 µCi, 662 keV photon.

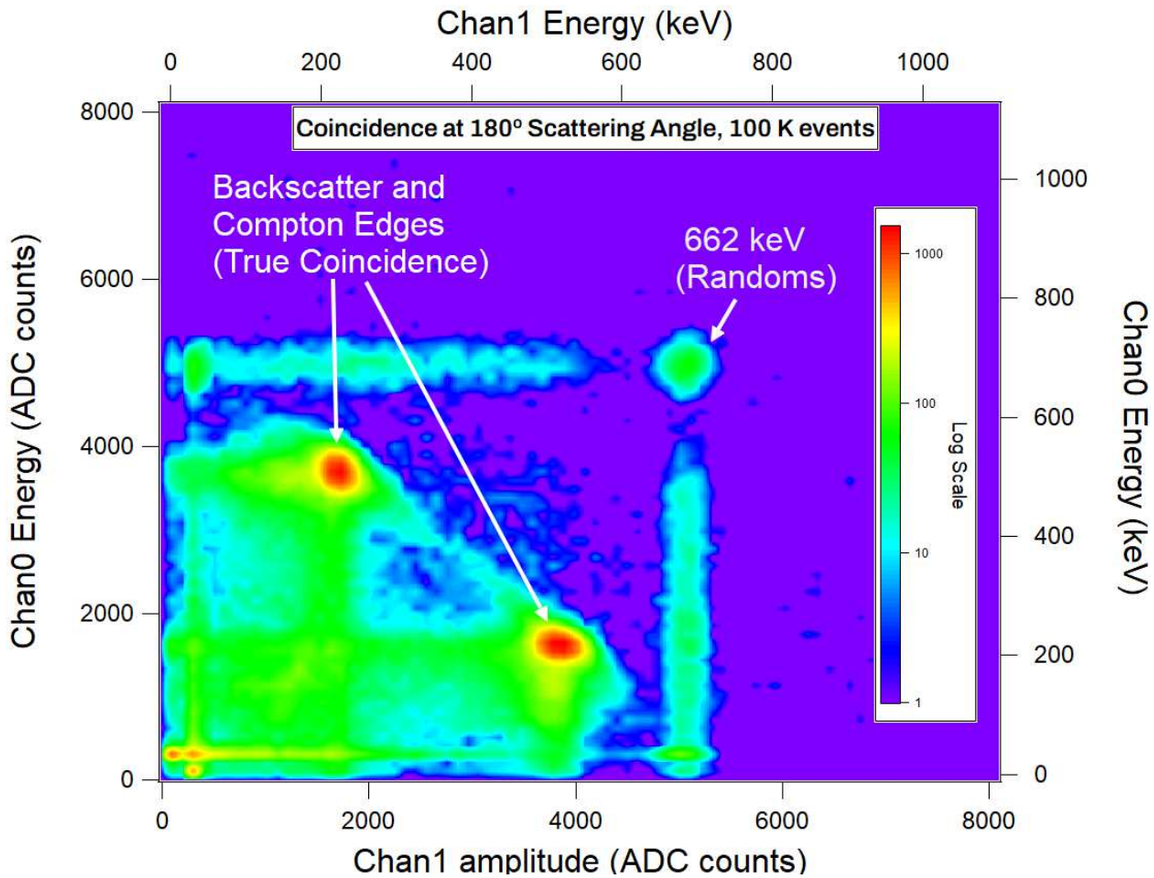




Education: Real Time Coincidence Demonstrates Compton Scattering

Your students will love it and they will learn a lot!

Coincidence scatter plot demonstrates true and random coincidences



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SkuTek Instrumentation
SkuTek.com

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